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SCIENCE DIRECT
Gait & Posture 23 (2006) 142–148
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Changes in foot-function parameters during the first 5 months after the onset of independent walking: a longitudinal follow-up study

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Received 14 July 2004; received in revised form 17 November 2004; accepted 12 January 2005

Abstract

Foot-function parameters (foot-contact patterns, oscillations of the centre of pressure (COP), peak pressures, relative vertical impulses and foot shape indices) were characterized in 10 toddlers at 1, 2, 3, 4, 6, 8, 10, 12, 16 and 20 weeks after the onset of independent walking. Significant changes were found in foot-contact patterns and COP oscillations. Improvements in balance, reflected in the decreased oscillations of the COP, coincided with changes in foot roll-over. These findings suggest that the development of a ‘‘heel-to-toe’’ roll-over pattern after 1 year of walking already starts early after the onset of independent walking. We could not identify any changes in load distribution underneath the plantar surface of the foot, suggesting that maturation of foot loading develops at a slower pace.

Keywords: Toddler; Gait; Foot-function; Pedobarography

1. Introduction

The foot serves three important biomechanical functions in bipedal gait. Firstly, the foot is important accommodating irregularities of the ground and maintaining balance. Secondly, it has to support weight and serve as a shock-absorber and thirdly, to generate forward movement, the foot has to transmit propulsive forces. In addition, its plantar surface plays a very important role in proprioception [2].

The adult human foot is well adapted to perform these functions. The longitudinal foot arch, primarily supported by the strong plantar aponeurosis, is an adaptation to resist load. The foot acts as a lever for transmission of propulsive forces on to the ground. This lever function is reflected in the typical ‘‘heel-to-toe’’ roll-over pattern observed in adult gait. The toddler’s foot anatomy differs from the adult foot (Fig. 1a and b) and is mainly characterized by its flexibility [3]. Around the age of 1, when toddlers normally start to walk, the foot skeleton consists of a number of partially ossified centres connected by soft tissue. Another important feature of toddler’s feet is the absence of a visible longitudinal foot arch. Development of the bony structure of the longitudinal arch only starts approximately 1 year after birth, when the toddlers have learned to stand upright and walk independently and lasts until the age of 5 [4,5]. To protect the fragile cartilaginous tissue, a fat pad is present underneath the foot plantar surface [6,7]. Ossification and changes in shape of the foot skeleton after the onset of independent walking coincide with resorption of this fat pad.

Some important differences between toddlers and adults in foot-function might be expected because of differences in anatomy and because balance and movement coordination are immature in young walkers [8]. Only a few studies have compared foot-function in toddlers [9–11] with that of adults. Foot-function is highly variable in this young age

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0966-6362/$ – see front matter
doi:10.1016/j.gaitpost.2005.01.003

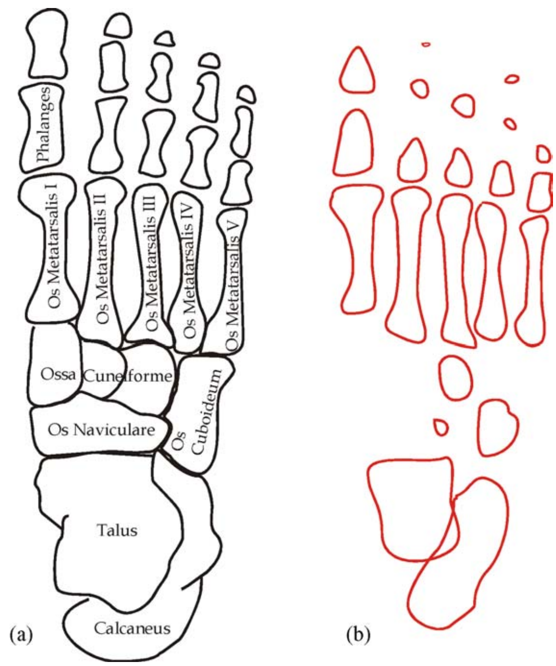


Fig. 1. (a and b) Compare the bony skeleton of the adult and toddler foot. In toddlers, the foot skeleton consists of several ossification centres surrounded by cartilage (after Tanner et al. [19]).

group. Variability is reflected in the absence of the typical ''heel-to-toe'' roll-over pattern, favoured in adult gait (Fig. 2). Hallemans et al. [11] have shown that toddlers with an ''independent-walking'' experience from 0 to 8 weeks had three different foot-contact patterns (Fig. 2). In initial forefoot-contact (IFC), first contact was made by the metatarsal heads, and then the midfoot and heel were placed on the ground. After a period of plantar contact, roll-over was initiated by heel-off and resulted in push-off by the hallux. In flat foot-contact (FFC), heel and forefoot were placed on the ground simultaneously. Again roll-over started with heel-off and ended in push-off by the hallux. In initial heel contact (IHC), a short initial contact occurred and the rest of the foot rapidly came into contact with the ground. Roll-over was identical to that seen in the IFC and FFC patterns. Balance problems in toddlers, suggested by their wide base of support, guard position of the arms and a prolonged phase of double support [12], was evident from the large oscillations of the centre of pressure (COP) [11] and the increase in areas contributing to load bearing [9]. Peak pressures underneath the heel and metatarsal heads are reduced when toddlers are compared to adults [9,11]. This can be explained partly by the slow average walking speed observed in toddlers. The soft character of the toddler's foot and the lower body weight to foot-contact-area ratio are also important factors reducing peak pressures. On the other hand, pressures are high underneath the midfoot region because of the absence of the longitudinal foot arch in toddlers [9,11].

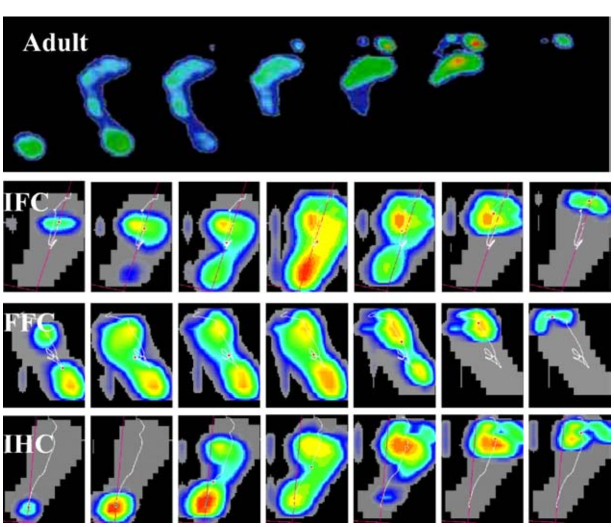


Fig. 2. The top panel shows subsequent pressure prints (recorded with a Footscan Pressure Pad) of a typical adult ''heel-to-toe'' roll-over pattern (left foot), starting with foot-contact made by the heel and ending in push-off by the hallux. High pressure areas are shown in red, low pressures in green and blue. The bottom panels show similar pressure recordings of the three different foot-contact patterns that can be observed in toddlers (IFC: initial forefoot-contact, right foot; FFC: flat foot-contact, left foot; IHC: initial heel contact, right foot). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

Based on kinematic observations, maturation of gait is divided into two phases: a first rapid development phase spanning the first 3–5 months after the emergence of independent walking and a second slower maturation phase lasting until the age of 8 [13]. The question arises whether maturation of foot-function follows the same time course. Changes in step–time parameters and joint kinematics occurring during this period can significantly alter loading and roll-over of the foot. Recently, Bertsch et al. [1] published a study on foot-function in toddlers in which they were followed for 1 year after the onset of independent walking. Pedobarographic recordings were made every 3 months. Changes, apart from general growth of the foot, leading to increased contact areas, were found in foot anatomy indicating an early development of the medial longitudinal arch. Improvements in motor control led to changes in roll-over and foot loading. After 1 year of walking, the flat-footed contact, observed at the onset of independent walking, was replaced by a heel-to-toe roll-over pattern. Loads were shifted from the midfoot to the fore- and hindfoot, leading to higher values of contact area, maximum force, impulse and peak pressures underneath these regions.

The 3 monthly data collection intervals from the study by Bertsch et al. [1] were not sufficient to detect early changes in foot-function occurring rapidly after the onset of independent walking. Therefore, we choose to perform a longitudinal study on foot-function focussing on the first 5 months of walking to investigate rapid changes in foot-function and our study can be considered complementary to the study of Bertsch et al. [1].

Table 1
Detailed information about the study subjects

No.	Gender	Pregnancy (weeks)	Birth weight (kg)	First steps (age in months)
1	Female	40	3.44	10
2	Male	40	2.66	13
3	Female	40	3.79	12
4	Female	41	3.41	14
5	Female	39	3.66	11
6	Female	38	3.65	15
7	Male	38	3.08	14
8	Female	40	3.55	11
9	Male	38	3.00	14.5
10	Female	42	3.98	12

Table 2
The number of successful footfalls for each individual, for each recording session

Session	1	2	3	4	5	6	7	8	9	10
Indices 1	4	1	4	5	2	5	5	5	2	5
Indices 2	4	3	4	5	–	5	5	2	4	3
Indices 3	–	–	–	4	3	3	–	4	5	4
Indices 4	–	4	5	5	5	3	–	4	5	3
Indices 5	–	–	–	5	5	5	5	5	5	5
Indices 6	2	5	4	–	5	4	5	5	5	5
Indices 7	4	–	–	4	5	5	5	3	5	5
Indices 8	4	4	5	5	5	5	5	5	5	5
Indices 9	–	–	5	5	5	5	5	-	5	5
Indices 10	5	5	5	5	5	5	5	5	5	5

2. Materials and methods

2.1. Subjects

Ten healthy toddlers (Table 1) were followed closely during the first 5 months after they started to walk independently. Written informed consent was obtained from the parents of the participating toddlers. Information on the toddlers' health and developmental history was gathered from a questionnaire and through the Denver Development Screening Test. When the toddlers performed their first independent two to three consecutive steps, the parents were asked to come to the gait laboratory, within that same week, for the first recording session. The following nine sessions were planned 2, 3, 4, 6, 8, 10, 12, 16 and 20 weeks thereafter. On each recording day, the toddlers' walking experience was calculated as the number of days after performing his/her first independent steps. Ideally, 100 recording sessions (10 toddlers × 10 developmental stages) were planned. However, for some toddlers data of one or more sessions were missing due to illness, holidays or lack of cooperation and so a total of 83 sessions were obtained.

2.2. Experimental set-up

A wooden walk-way with a built-in pressure pad (0.5 m × 0.4 m, 250 Hz, 3 sensors/cm^2, Footscan Int., Olen, Belgium) was coupled to a force platform (0.5 m × 0.4 m, 250 Hz, AMTI, MA, USA). This enabled an on-line calibration of the pressure data to the force recordings. For each sample the integrated pressures over the entire mat should equal the vertical force data recorded by the force plate. The set-up was controlled by the Footscan Software (Version 6.3.5 for Antwerp, Macintosh edition). The toddlers were encouraged to walk barefoot over the platform at a self-selected speed. From each trial one successful footfall was selected. Selection criteria were: only the toddler's feet contacted the recording platform, the entire plantar surface of the foot was visible during a complete roll-over and trials in which the toddlers stopped or turned were discarded. Usually we obtained three to five successful footfalls for each recording session (Table 2).

2.3. Foot-function parameter

For each individual session, the number of IFC, FFC and IHC was counted and expressed as a percentage of the total number of footfalls analyzed. The relative duration of the initial contact phase (ICF—from initial heel contact to first metatarsal contact), forefoot-contact phase (FFCF—from first metatarsal contact to last metatarsal contact), foot-flat phase (FFF—from last metatarsal contact to heel-off) and the push-off phase (POF—from heel-off to push-off by the hallux) as defined by De Cock et al. [14] were determined on the pressure–time curves and compared to the normal values in adult gait (based on the young adult data set from Blanc et al. [15]).

From oscillations of the COP, an index (R_x and R_y) can be calculated to quantify stability during foot-contact. The R_x and R_y indices give a numeric value for the deviation of the COP from the longitudinal axis of the foot (defined as a straight line running from the middle of the heel to the middle of the 2nd and 3rd metatarsal head; (Fig. 3a—formulae (1) and (2)).

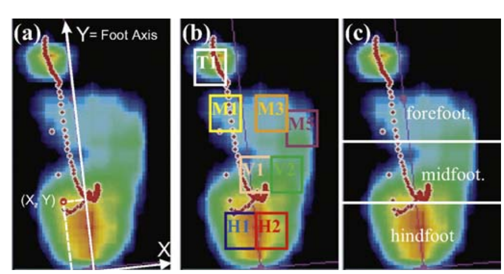


Fig. 3. (a) A peak pressure footprint (a virtual image that is made by superimposing all pressures recorded during foot-contact) that is used to calculate the R_x and R_y indices. A coordinate system is defined on each selected footprint with the *Y*-axis along the longitudinal axis of the foot and the *X*-axis perpendicular to it. In each frame, the COP is assigned (x_i, y_i) coordinates, relative to this reference frame that are used to calculate R_x and R_y according the formula (1) and (2). (b) The positions of the selected areas (1.4 cm × 1 cm) for retrieving pressure distribution data. H1: medial heel, H2: lateral heel, V1: medial midfoot, V2: lateral midfoot, M1: medial metatarsal heads, M2: central metatarsal heads, M3: lateral metarsal heads and T1: hallux. (c) How the forefoot, midfoot and hindfoot regions are selected on the peak pressure footprint. RVI are calculated from the vertical force measured underneath the entire region.

$$R_x = \frac{\sum \sqrt{(x_{i+1} - x_i)^2}}{\text{foot length}} \quad (1)$$

$$R_y = \frac{\sum \sqrt{(x_{i+1} - x_i)^2}}{\text{foot length}} \quad (2)$$

If the COP closely follows the foot axis during roll-over $R_x \sim 0$ and $R_y \sim 1$. If $R_y > 1$ the COP shows large forward–backward oscillations underneath the plantar surface contact area; if $R_y < 1$ roll-over is reduced as, for example, in tip toeing.

Peak pressures during foot-contact were determined underneath the heel, the midfoot, the metatarsal heads and the hallux (Fig. 3b). The selected areas had a size of 1.4 cm × 1 cm and were semi-automatically detected on the peak pressure footprint by the Footscan Software. An investigator checked the positioning of the areas and corrected when necessary.

To calculate relative vertical impulses (RVI) the foot was divided into forefoot (anterior 1/3 of foot length), midfoot (middle 1/3rd of foot length) and hindfoot (posterior 1/3rd of foot length—Fig. 3c). RVI (Eqs. (3)–(5)) gives information on the relative load of a distinct anatomical area of the foot in comparison to the total loading of the foot [9]:

$$\mathrm{RVI}_{\text{forefoot}} = \frac{\int_{\text{foot contact}}^{\text{foot off}} F_{\text{forefoot}}\,\mathrm{d}t}{\mathrm{RVI}_{\text{forefoot}} + \mathrm{RVI}_{\text{midfoot}} + \mathrm{RVI}_{\text{rearfoot}}} \quad (3)$$

$$\mathrm{RVI}_{\text{midefoot}} = \frac{\int_{\text{foot contact}}^{\text{foot off}} F_{\text{midefoot}}\,\mathrm{d}t}{\mathrm{RVI}_{\text{forefoot}} + \mathrm{RVI}_{\text{midfoot}} + \mathrm{RVI}_{\text{rearfoot}}} \quad (4)$$

$$\mathrm{RVI}_{\text{rearfoot}} = \frac{\int_{\text{foot contact}}^{\text{foot off}} F_{\text{rearfoot}}\,\mathrm{d}t}{\mathrm{RVI}_{\text{forefoot}} + \mathrm{RVI}_{\text{midfoot}} + \mathrm{RVI}_{\text{rearfoot}}} \quad (5)$$

with F_{forefoot} the vertical force component measured underneath the entire forefoot, likewise for F_{midfoot} and F_{rearfoot}.

To identify structural changes, foot shape indices (width of the midfoot at smallest point/length of the foot [1]) were determined on all the selected footfalls. There is a good relationship between the arch index determined on plantar pressure recordings and radiographic arch parameters [16].

2.4. Statistical analysis

To identify changes in foot-contact patterns in relation to walking experience, the occurrence of IFC, FFC and IHC counted for each individual were averaged per session. Changes in the prevalence of IFC, FFC and IHC were investigated using a Pearson rank correlation. Significance was set at $p < 0.05$.

Changes in the stability indices, peak pressures, RVI and foot shape indices with increasing walking experience were investigated using a linear regression model. Since trial-to-trial consistency within each session was low to moderate (ICC: 0.07–0.53) data from the different number of trials in each session could not be averaged. Therefore, all observations from each trial were used and the repeated measure structure of the data was taken into account. This was performed using a mixed model type of analysis. For details we refer to Molenberghs and Verbeke [17] for a general outline. Interdependence occurred at two levels. Firstly, at the lowest level, within session observations from the different trials were interdependent and we assumed a compound symmetry correlation structure (i.e., equal correlation among the different trials within each session). At the level of the individual, interdependence originated from the fact that different sessions of data were obtained within a set of 10 individuals. Individual deviations from the average model were incorporated in the analysis using random effects. In this way, among individual variation in the associations between the foot-function parameters and walking experience could be determined. The interdependence of the data of the individual was incorporated in the model and the degrees of freedom of tests of population level slopes determined. Significance of random effects was determined using the likelihood ratio test and slopes tested using F-tests. A quadratic model with random intercept and slopes (both linear and quadratic) was used as full model, and non-significant terms were eliminated using a backward selection procedure. Removal of non-significant terms started with the quadratic terms.

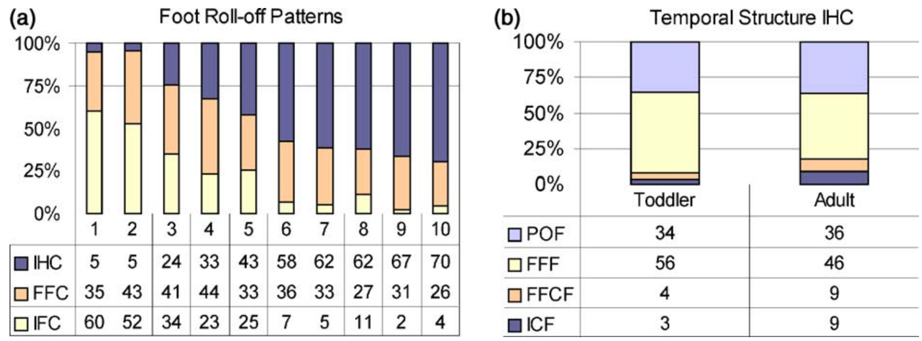
Variability of the repeated measures for each session was tested by calculating coefficients of variations (COV) for the stability indices, peak pressures and RVI. Changes in COV as a function of walking experience were tested using a regression model to identify a potential trend towards a more consistent gait pattern. A similar mixed regression model was used as outlined in the previous paragraph, yet without interdependence of within session observations because data from each session yielded only one observation.

Statistical significance was set at $p < 0.05$. All statistical tests were carried out using the SAS Software Package (for Windows V8).

3. Results

3.1. Foot-contact patterns

Fig. 4a shows the occurrence of IFC, FFC and IHC during each session. At the onset of independent walking primarily IFC and FFC were observed. IHC was seen in only 5% of the analysed footfalls. With increasing walking experience, the prevalence of IFC decreased significantly ($r = -0.54$; $p < 0.0001$) while a significant increase in IHC ($r = 0.64$; $p < 0.0001$) occurred. After 5 months of independent walking, IFC was observed in less than 5 % of the analyzed footfalls while IHC represented the greatest of foot-contact pattern (70% of all footfalls). A moderate decrease could be identified in the prevalence of FFC ($r = -0.27$; $p = 0.015$).



	1	2	3	4	5	6	7	8	9	10
IHC	5	5	24	33	43	58	62	62	67	70
FFC	35	43	41	44	33	36	33	27	31	26
IFC	60	52	34	23	25	7	5	11	2	4

	Toddler	Adult
POF	34	36
FFF	56	46
FFCF	4	9
ICF	3	9

Fig. 4. (a) The prevalence (expressed in % of analysed footfalls) of IFC, FFC and IHC during each of the 10 recording sessions is shown. Initially, IFC and FFC are dominantly observed. With increasing walking experience, the number of IFC decreases while IHC becomes dominant. (b) The IHC observed in toddlers still differs from the adult ''heel-to-toe'' roll-off pattern. Due to stability problems in new walkers, the ICF and FFCF are short and the FFF is prolonged (adult values derived from the study of Blanc et al. [15]).

Fig. 4b compares the temporal structure of the ''heel-to-toe'' roll-over between new walkers and adults. The ICF and FFCF were significantly shorter in toddlers ($t = -14.32$; d.f. = 138; $p = 0.000$ and $t = -7.21$; d.f. = 138; $p = 0.000$) while the FFF was prolonged ($t = 8.73$; d.f. = 138; $p = 0.000$). No differences could be identified in duration of the POF between adults and toddlers ($t = -1.38$; d.f. = 138; $p = 0.17$).

3.2. Oscillations of the COP

R_x and R_y indices showed a statistically significant relationship with walking experience (Fig. 5a and b). In a first analysis, including all individuals, we found a highly significant random intercept ($p < 0.0001$) for R_x. It turned out that the first observations of individuals 1 and 2, recorded at the onset of independent walking were significantly different from all other results. Since this violated the normality assumption, these individuals were removed from the analysis. A similar pattern was observed for R_y, where only individual 1 appeared to cause normality problems. We, therefore, decided to exclude data from this individual here, as well. Based on the remaining 8 and 9 individuals, respectively, both R_x as R_y showed a second-order relationship with walking experience ($R_x = 0.43 - 0.003 \times \times \text{WE} + 0.000012 \times \text{WE}^2$ and $R_y = 1.32 - 0.008 \times \text{WE} + 0.000042 \times \text{WE}^2$). All p-values of the intercepts and slopes in these analyses are <0.001. None of the random effects were statistically significant indicating that all individuals followed the same trend.

3.3. Peak pressures and relative vertical impulses

Peak pressures were highly variable between different trials of the same individual. In general, peak pressures were largest under the heel (6.58 ± 3.83 N/cm^2), followed by the central (5.86 ± 2.25 N/cm^2) and medial (4.62 ± 2.14 N/cm^2) metatarsal heads and first toe (4.10 ± 2.29 N/cm^2). Even pressures underneath the midfoot were relatively large (4.24 ± 1.69 N/cm^2). The regression model showed no relationship between walking experience and peak pressures. Considering the RVI, load seemed to be almost evenly

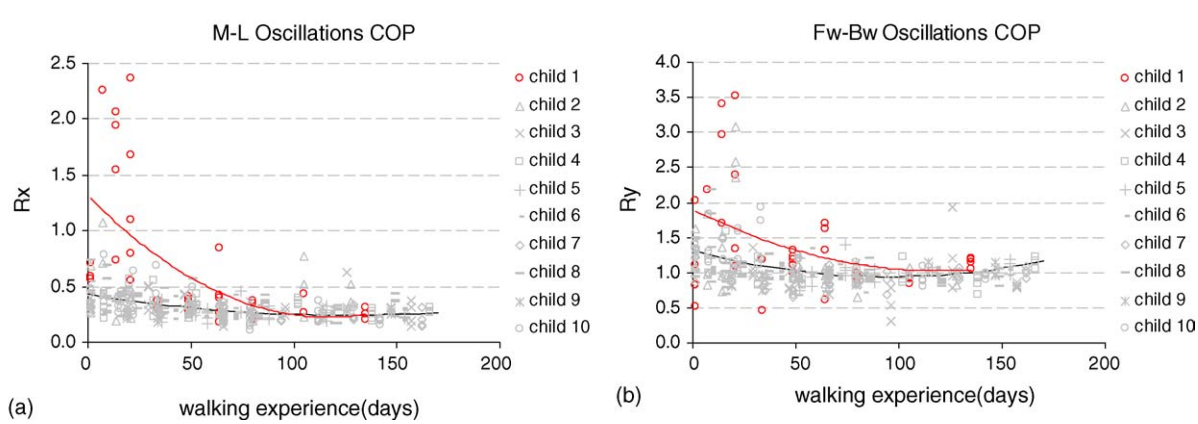


Fig. 5. R_x and R_y indices are plotted as a function of walking experience (expressed in days after the onset of independent walking). Both stability indices show a second-order relationship with walking experience. ($R_x = 0.43 - 0.003 \times \text{WE} + 0.000012 \times \text{WE}^2$ and $R_y = 1.32 - 0.008 \times \text{WE} + 0.000042 \times \text{WE}^2$). Individual 1 (shown in red) differs significantly from the others in intercept for both R_x and R_y. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

distributed over the entire plantar surface of the foot. During contact, the forefoot bore 36.4 ± 40% of the load, the midfoot 22.3 ± 20 % and the hindfoot 41.4 ± 36 %. No relationship was found between walking experience and RVI.

3.4. Foot shape index

On average the foot shape index equalled 31 ± 6%. No changes were found in foot shape index as walking experience increased.

3.5. Variability of the repeated measurements

Intra-individual variation in toddler foot-function parameters was moderate to large (COV: 23–76%). The regression model showed no change in COV with increasing walking experience.

4. Discussion

We managed to follow 10 toddlers intensively for 5 months, immediately after they performed their first independent steps. Unfortunately some missed out on one or more of the recording sessions. In 3 of the 10 participating toddlers, we lacked data from the first 2–3 weeks of independent walking. Theoretically, this could influence the average trend, but since the random effects model showed that these individuals did not differ from the others, we feel this was not the case.

Ten toddlers was a small group from which to draw conclusions about general trends in foot-function for normally developing toddlers. But since the random effect model showed that in 9 of the 10 toddlers foot-function parameters evolved similarly, we feel that our data contribute substantially to the understanding of early changes in foot-function in toddlers. Individual 1 did differ significantly from the others considering the stability indices at the onset of independent walking. This could be because individual 1 was much younger than the other toddlers (only 10 months old) when she performed her first independent steps.

This study confirms the foot-contact pattern findings of Bertsch et al. [1], which showed a trend from FFC to heel-to-toe roll-over with increasing walking experience. We observed that maturation of roll-over starts already very early after the onset of independent walking. It is important to note however that the IHC we observed in toddlers differs from the adult ‘‘heel-to-toe’’ roll-over in duration of the four sub-phases. In toddlers, the ICF and FFCF are very short while the FFF is prolonged. Most likely this results from balance problems. Toddlers probably try to increase the amount of time during which the entire plantar surface is in contact with the ground. With increasing walking experience there is a slight increase in duration of the ICF ($R = 0.335$; $p = 0.010$) suggesting improvements in balance control.

At the onset of independent walking balance control is poor leading to large oscillations of the COP underneath the plantar surface of the foot. As balance control improves, the oscillations of the COP gradually decrease. However, the foot is still placed relatively flat on the ground and the toddler does not yet use the entire foot during roll-over. Further improvements in balance control lead to a further evolution towards a heel-to-toe roll-over pattern (COP_y evolves towards 1). From improvements in balance control and changes in foot roll-over, we expected a gradual decrease of the R_x and R_y scores with increasing walking experience evolving slowly towards mature values instead of the second-order relationship we observed, which might be an artefact resulting from the high variability in toddler gait.

From our observations, it can be hypothesised that improvements in balance control are closely related to foot roll-over and walking dynamics. At the onset of independent walking, balance control is poor and the toddler takes small steps using a forefoot-contact or flat foot-contact. As balance improves, a heel contact pattern emerges, very likely contributing to an increased step length, as heel contact requires adequate knee extension, thereby improving the walking dynamics.

Peak pressures and RVI showed an equal load distribution over the entire foot plantar surface. Comparison of the average peak pressures we recorded in this study to pressures reported in previous studies [1,9] shows that the values we obtained were relatively small (e.g., peak pressures under the heel reported in literature have a magnitude from 11.9 ± 6.1 N/cm^2 [9] to 12.6 ± 4.4 N/cm^2 [1] in comparison to our value of 6.58 ± 3.83 N/cm^2). However, variation was substantial and the data reported in the literature fall within the range of pressures we observed. Possibly the observed differences, as well as the wide variation in pressure data, can be largely explained by variability in walking speed [18]. The RVI in our study are of comparable magnitude with literature data; Bertsch et al. [1] reported RVI of 26%, 31% and 43% for the hindfoot, midfoot and forefoot, respectively.

Despite improvements in balance control and changes in roll-over, no significant change was found in peak pressures or loading of the foot plantar surface during the first 5 months of independent walking. Bertsh et al. [1] found that after 1 year of independent walking, load was shifted away from the midfoot towards the fore- and hindfoot. They attributed this to an early development of the medial longitudinal arch. Given this relationship between foot loading and foot morphology, the absence of significant changes in peak pressures and RVI in this study can be explained by the absence of changes in foot morphology. But Bertsch et al. [1] in their study of 42 toddlers found significant changes in foot arch after 3 months of independent walking but they also reported large inter-individual differences in foot shape and growth. The variation in foot shape was probably too large to observe any significant changes within our small sample size.

The COV showed that intra-individual variations was relatively large in this study and an absence of change in COV as walking experience increased is consistent with the findings of Bertsch et al. [1] and indicates that a consistent foot-function pattern has not yet developed after 5 months of independent walking.

5. Conclusion

Changes in foot-function were observed early after the onset of independent walking. After 5 months, a ‘‘heel-to-toe’’ roll-over pattern was seen in the majority of footfalls. A dramatic decrease in oscillations of the COP was observed but no changes occurred in loading of the foot’s plantar surface. This suggests that large changes in walking dynamics coincide with improvements in balance control and occur rapidly after the onset of independent walking. However, subtle morphological changes of the foot that can affect load distribution evolve at a much slower pace.

Acknowledgements

We thank the toddlers and their parents who participated in this research. We also thank the Department of Health Care from the Hogeschool Antwerpen (Belgium) for their logistic support. This study was funded by the Fund for Scientific Research—Flanders by a personal grant for A.H. and by a BOF project for P.A.

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